Measurements of time dependent CP asymmetry in $B \to VV$ decays with BELLE

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A study of CP violation in $B \to J/\psi K^*(K_S^0\pi^0)$ decays by time dependent angular analysis is discussed. Status of time independent analyses for other $B \to VV$ decays is also reported. The data used for the analyses are taken with the Belle detector at KEK.

1. Introduction

There are three helicity states in $B \to VV$ decays. Although one of the states is a pure CP even state, CP even and odd states are mixed in other states and the observed CP asymmetry is diluted. By studying decay angles of final state particles, it is possible to project out each CP state in a statistical way. A theoretical expression of differential time-angular decay rate of $B \to VV$ decays consists of components corresponding to three helicity states and also to the interference between them. Each term is expressed as a product of an angular term and an amplitude term. The amplitude term contains CP violating phase(s) as a function of Δt, the decay time difference between two B mesons from an $\Upsilon(4S)$ decay. A fit of the expression for the measured decay angles and Δt gives the determination of the CP violating phase(s). The interference terms are also rich sources of various interesting physics such as the $\cos 2\phi_1$ measurement in $B^0 \to J/\psi K^{*0}(K_S^0\pi^0)$ decays, and the simultaneous determination of r and $\sin(2\phi_1+\phi_3)$ in $B^0 \to D^{*-}\rho^+$ decays where r is the ratio of doubly-Cabibbo-suppressed mode to Cabibbo favored mode contributing to the decay.

In this talk, a study of time dependent angular analysis for $B \to J/\psi K^*(K_S^0\pi^0)$ is discussed. Also reported is status of angular analyses for $B^0 \to D^{*+}D^{*-}$ and $B^0 \to D^{*-}\rho^+$. The data used in the analyses are taken with the Belle detector[1] in the KEKB accelerator[2]. The KEKB accelerator consists of two separate rings for electrons and positrons. The energies are set at 3.5 GeV for positrons and 8.0 GeV for electrons, respectively. These two beams are collided at the interaction point to produce $\Upsilon(4S)$ in motion for the measurement of Δt. The peak luminosity of the machine has reached $7.4 \times 10^{33} cm^{-2} sec^{-1}$ which is the current world record. The total integrated luminosity up to now is $89.1 fb^{-1}$. The Belle detector is placed at the interaction point of the KEKB accelerator. It is a general-purpose detector with a wide angle coverage featuring a particle identification using the Aerogel Cherenkov Counter assembly. The data sample used in the analyses corresponds to an integrated luminosity of 78 fb^{-1} taken on the $\Upsilon(4S)$ resonance.

2. Time dependent angular analysis for $B^0 \to J/\psi K^*(K_S^0\pi^0)$[3]

Candidate B^0 mesons are reconstructed by selecting events with a J/ψ identified from a pair of oppositely-charged leptons and a K^* from a pair of K_S^0 and π^0 candidates. The beam-constrained mass (M_{bc}), which is the invariant mass of a reconstructed J/ψ and K^* calculated taking the energy to be the beam energy, is required to be in the range $5.27 - 5.29$ GeV/c^2 and the energy difference between B candidate and the beam energy (ΔE) to satisfy -50 MeV $< \Delta E <$ 30 MeV. To eliminate slow π^0 backgrounds, the angle of

the kaon with respect to the K^* direction in the K^* rest frame, $\cos\theta_{K^*}$, is required to satisfy $\cos\theta_{K^*} < 0.8$. When an event contains more than one candidate passing the above requirements, the combination for which ΔE is closest to zero is selected. The number of events remaining after the selection is 104.

The time dependent angular distribution of the decay is described as[4]:

$$\frac{d^4\Gamma(\theta_{tr},\phi_{tr},\theta_{K^*},\Delta t)}{d\cos\theta_{tr}d\phi_{tr}d\cos\theta_{K^*}d\Delta t} = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\sum_{i=1}^{6} g_i(\theta_{tr},\phi_{tr},\theta_{K^*})a_i(\Delta t) \quad (1)$$

where g_i are the angular terms and a_i are amplitude terms. τ_B is the lifetime of a B^0 meson. The g_i are expressed as:

$$g_1 = 2\cos^2\theta_{K^*}(1-\sin^2\theta_{tr}\cos^2\phi_{tr}) \quad (2)$$
$$g_2 = \sin^2\theta_{K^*}(1-\sin^2\theta_{tr}\sin^2\phi_{tr}) \quad (3)$$
$$g_3 = \sin^2\theta_{K^*}sin^2\theta_{tr} \quad (4)$$
$$g_4 = \frac{-1}{\sqrt{2}}\sin 2\theta_{K^*}\sin^2\theta_{tr}\sin 2\phi_{tr} \quad (5)$$
$$g_5 = \sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr} \quad (6)$$
$$g_6 = \frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin 2\theta_{tr}\cos\phi_{tr} \quad (7)$$

where θ_{tr}, ϕ_{tr} and θ_{K^*} are the decay angles defined in the transversity basis[5]. The a_i are

$$a_1 = |A_0|^2(1+\eta\sin 2\phi_1\sin\Delta m\Delta t) \quad (8)$$
$$a_2 = |A_\parallel|^2(1+\eta\sin 2\phi_1\sin\Delta m\Delta t) \quad (9)$$
$$a_3 = |A_\perp|^2(1-\eta\sin 2\phi_1\sin\Delta m\Delta t) \quad (10)$$
$$a_4 = Re(A_\parallel^* A_0)(1+\eta\sin 2\phi_1\sin\Delta m\Delta t) \quad (11)$$
$$a_5 = \eta Im(A_\parallel^* A_\perp)\cos\Delta m\Delta t - \eta Re(A_\parallel^* A_\perp)\cos 2\phi_1\sin\Delta m\Delta t \quad (12)$$
$$a_6 = \eta Im(A_0^* A_\perp)\cos\Delta m\Delta t - \eta Re(A_0^* A_\perp)\cos 2\phi_1\sin\Delta m\Delta t \quad (13)$$

where Δm is the $B^0 - \overline{B^0}$ mixing parameter. η is +1 for B^0 while -1 for $\overline{B^0}$. A_0, $A_\parallel$ and $A_\perp$ are the complex decay amplitudes for three helicity states in the transversity basis. Two CP violation parameters, $\sin 2\phi_1$ and $\cos 2\phi_1$, appear in the formula. The values of these parameters are determined by fitting the formula to the measured angles and Δt, taking into account the detection efficiency and background. The fit is done using an unbinned maximum likelihood method. The probability density function for an event is defined as

$$\begin{aligned} PDF = {} & f_{sig}(M_{bc})\epsilon(\theta_{tr},\phi_{tr},\theta_{K^*}) \\ & \times \frac{d^4\Gamma(\cos\theta_{tr},\phi_{tr},\cos\theta_{K^*},\Delta t)}{d\cos\theta_{tr}d\phi_{tr}d\cos\theta_{K^*}d\Delta t} \\ & + \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \\ & \times \{\sum_i f_{cf}^i(M_{bc})ADF_{cf}(\theta_{tr},\phi_{tr},\theta_{K^*}) \\ & + f_{nr}(M_{bc})ADF_{nr}(\theta_{tr},\phi_{tr},\theta_{K^*})\} \\ & + \delta(\Delta t)f_{combi}(M_{bc})ADF_{combi}(\theta_{tr},\phi_{tr},\theta_{K^*}). \end{aligned} \quad (14)$$

f_{sig}, f_{cf}, f_{nr} and f_{combi} are fractions of the signal, cross feed, non-resonant production, and combinatorial background as a function of M_{bc}, respectively, while ADF_{cf}, ADF_{nr} and ADF_{combi} are corresponding angular shape functions. ϵ is a three dimensional detection efficiency function for the signal. The determinations of these functions and the decay amplitudes are described in ref.[6]. Phases in the amplitudes are chosen so as to conserve s-quark helicity[7]. The τ_B and Δm are fixed at the PDG values in the fit. The flavor tagging procedure[8] gives the flavor of tag-side B meson q and the probability of wrong tag w. To account for the effect of the wrong tagging in the data, η is replaced with $-q(1-2w)$ in the PDF.

Each term in the PDF is then convolved with appropriate resolution functions[9] separately for the signal, the backgrounds with a B^0 lifetime and the combinatorial background with a $\delta(\Delta t)$ function shape. The parameters in the resolution functions are calculated event by event. From the fit to the data, we obtain $\sin 2\phi_1 = 0.13 \pm 0.51 \pm 0.06$, and $\cos 2\phi_1 = 1.40 \pm 1.28 \pm 0.19$. The systematic errors include uncertainties in the resolution parameters, wrong tagging fractions, decay amplitudes, background fractions and shapes, and others. The distributions of Δt measured for the samples tagged as $q = +1$ and -1 are shown in Figure 1 together with the predictions by the PDF with obtained CP parameter values.

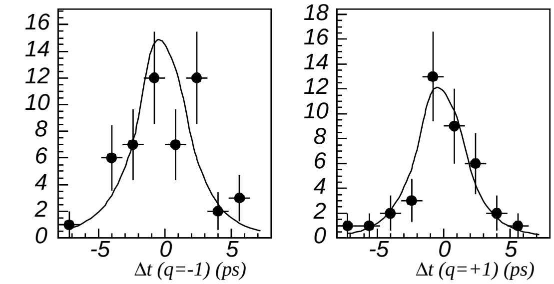

Figure 1. Δt distributions for samples tagged as $q = +1$ and -1. The lines show the predictions by the PDF with determined CP parameter values.

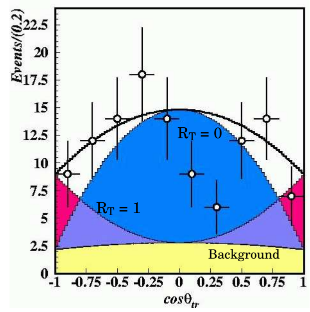

Figure 2. Distribution of $\cos\theta_{tr}$ for $B^0 \to D^{*+}D^{*-}$ candidates.

3. Time independent angular analyses

The time dependent angular analysis is applicable for other $B \to VV$ decays such as $B^0 \to D^{*+}D^{*-}$, $D^{-*}\rho^+$ and $\rho^+\rho^{-1}$ for the determination of CP violating phases including those other than ϕ_1. Time dependent analyses for these modes are still in preparation and the status of time independent(integrated) analyses is reported here. The measurement of the decay amplitudes by the time independent angular analysis is essential for the determinations of the CP violating phases.

3.1. $B^0 \to D^{*+}D^{*-}$

The reconstruction of a D^* is performed using a $D\pi$ decay with a subsequent D decay into $K\pi, K\pi\pi, K\pi\pi\pi, KK$ and $KK\pi$. A D meson is identified when the invariant mass of decay particles is within 3 to 6 σ from the nominal D mass depending on the decay mode. A D^* is reconstructed by calculating the mass difference $M(D\pi) - M(D)$ and those satisfy the difference within $3.0MeV(D^0)$ or $2.25MeV(D^+)$ are identified as D^*. The candidate B mesons are selected by applying $M_{bc} > M_{B^0} - 3\sigma$ and $|\Delta E| < 40MeV$.

The distribution of the transversity angle[5] is measured in the selected B^0 candidates as shown in Fig. 2. The distribution can be expressed as a function of the fraction of CP-odd component (R_T) as

$$\frac{d\Gamma}{d\cos\theta_t r} = \frac{3}{4}(1 - R_T)\sin^2\theta_{tr} + \frac{3}{2}R_T\cos^2\theta_{tr}. \quad (15)$$

The predictions given by this formula for cases with $R_T = 0$ and $R_T = 1$ are also shown in the figure. As seen, the distribution of the data is close to the prediction with $R_T = 0$.

3.2. $B^0 \to D^{*-}\rho^+$

The reconstruction of a D^{*-} is performed in a similar manner as described above. A ρ^+ is reconstructed from a pair of π^+ and π^0 candidates. The M_{bc} of a pair of reconstructed D^* and ρ is required to be in the range 5.27 - 5.29 GeV/c^2 to and ΔE to satisfy $-100 < |\Delta E| < 50MeV$.

The time independent angular distribution is studied using the helicity basis angles[4]. The decay rates as a function of each of three projected angles (two helicity angles θ_i where $i = 1, 2$, and an angle between two decay planes χ) can be expressed as

$$\frac{d\Gamma}{d\cos\theta_i} = \frac{4\pi}{3}|A_0|^2\cos^2\theta_i + \frac{2\pi}{3}(|A_\perp|^2 + |A_\parallel|^2)\sin^2\theta_i, \quad (16)$$

$$\frac{d\Gamma}{d\chi} = (\frac{4}{9}|A_0|^2 + \frac{8}{9}|A_\perp|^2)\sin^2\chi + (\frac{4}{9}|A_0|^2 + \frac{8}{9}|A_\parallel|^2)\cos^2\chi + \frac{8}{9}Im(A_\parallel^* A_\perp)\sin 2\chi \quad (17)$$

[1]The angular analysis for $B^+ \to \rho^+\rho^0$ is covered in other talk[10].

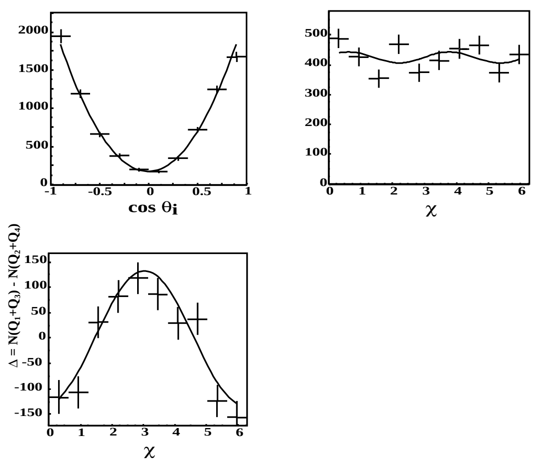

Figure 3. Distributions of angles used in the angular analysis for $B^0 \to D^{*-}\rho^+$ candidates. The distributions are corrected for the acceptance and background contaminations.

where A_0, $A_\parallel$ and $A_\perp$ are the decay amplitudes in the transversity basis. In addition, we also used χ-differential decay rates projected in 4 quadrants of a $\theta_1 - \theta_2$ plane (angular regions from 0 to $\pi/2$ and $\pi/2$ to π for each of them) to observe the effects in interference terms. The difference in the decay rates between two diagonally-summed quadrants (Δ) can be written as

$$\frac{d\Delta}{d\chi} = -\frac{8}{9\sqrt{2}} Im(A_0^* A_\perp)\sin\chi + \frac{8}{9\sqrt{2}} Re(A_0^* A_\parallel)\cos\chi. \tag{18}$$

Fig. 3 shows the distributions of $\cos\theta_i$ (θ_1 and θ_2 distributions are added), χ, and $\Delta(\chi)$. The measurement of the decay amplitudes is now in progress by fitting these distributions with the theoretical formula given above considering effects of the detector acceptance and background contaminations.

4. Summary

A full time dependent angular analysis is performed for $B^0 \to J/\psi K^{*0}(K_S^0\pi^0)$ decays collected with the Belle detector at KEK B-factory. The decay angles in the transversity basis (θ_{tr}, ϕ_{tr} and θ_{K^*}) and the decay time difference of two B mesons (Δt) are measured for each event with the determination of the flavor of tag-side B meson. The values are fitted to the theoretical distribution using an unbinned maximum likelihood method considering the effects of detector acceptance, background contamination, Δt resolution and wrong flavor tagging. From the fit, two CP violation parameters are determined to be $\sin 2\phi_1 = +0.13 \pm 0.51 \pm 0.06$, and $\cos 2\phi_1 = +1.40 \pm 1.28 \pm 0.19$. If we take the s-quark helicity conservation choice of the amplitude phases and the $\sin 2\phi_1$ value measured using other decay modes ($0.72 \pm 0.07 \pm 0.04$)[9], the obtained sign of $\cos 2\phi_1$ suggests the $2\phi_1$ to be in the range $0^\circ < 2\phi_1 < 90^\circ$ and the other choice of $2\phi_1 \geq 90^\circ$ is not preferred although the current statistics is not enough to conclude this.

A time independent angular analysis for other decay modes, $B^0 \to D^{*+}D^{*-}$, $B^0 \to D^{*-}\rho^+$, and $B^+ \to \rho^+\rho^0$, are now being performed.

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